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Full Length Article

Friction and wear behaviors of molybdenum disulfide nanosheets under normal electric field

Yuanming Zeng[a], Feng He[b], Quan Wang[a,c,*], Xiaohong Yan[a], Guoxin Xie[b,*]

[a] School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China
[b] State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[c] State Key Laboratory of Transducer Technology, Chinese Academy of Sciences, Shanghai 200050, China

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ABSTRACT

The friction and wear behavior of micro-molybdenum disulfide (MoS_2) is studied by atomic force microscope (AFM), and both positive and negative bias are applied to the conductive probe and substrate. The experimental results show that the nano-friction between MoS_2 nano-sheets and AFM probes can be regulated by an external normal electric field. Friction force will increase with the increase of the external bias. The maximum bias has a threshold value. If the bias exceeds the threshold, it will promote the formation of MoS_2 charge transfer and accelerate oxidation during the friction process. The tuning value of the friction force can be increased by 2 times, compared with the friction force under the condition of non-bias. We propose a feasible and valuable strategy to adjust the friction characteristics of the MoS_2 system, which provides great significance to understand and control the nano-friction in the practical application.

1. Introduction

Two dimensional transition-metal dichalcogenides (TMDCs) are a kind of layered structure materials which are very similar to graphene [1]. Molybdenum disulfide (MoS_2) is a two-dimensional semiconductor material with good compressive strength and wear resistance, excellent adhesion, lower friction coefficient. Therefore, it has lubrication performance, which can be used as solid lubricant in the harsh environment such as high temperature and pressure work, thus prolonging the service life of the equipment. And 2D materials are often used as additives for composites to study friction and wear properties [2–4].

Their tribological properties remain to be studied, compared with other properties of 2D materials, such as electronic, optical, mechanical, chemical and thermal properties [5]. But there are many studies which only focus on the traditional methods to change the external temperature or humidity for the study of friction and wear problems [6–8]. It is found that MoS_2 is prone to be oxidized when friction occurs under high temperature and humidity conditions [9]. With the development of modern industrial technology, more and more mechanical systems rely on electromagnetic technology to control and operate the whole equipment. The key sliding parts of these mechanical equipments, such as maglev train, electric motor brush, high-speed rail contact wire and skateboard, high-power power transmission of the switch contactor, are related to the friction and wear problem under electromagnetic action. At the same time, because of the difference of the free electron density and the electron escaping power, the electromagnetic field is generated, which will excite the electromagnetism effect of the frictional interface during the friction pair in the process of contacting or occurring relative motion. MoS_2 is widely utilized as solid lubricant in micro-nano mechanical devices [10–12]. For example, a MEMS actuator (electrostatic lateral output motor) operated in a vacuum is rapidly invalidated due to catastrophic wear of device components (micro-particles). It can be employed to reduce the adhesion and friction between the contact surfaces in the MEMS/NEMS device, while protecting the coating surface. During the process of work, the effect of external electric field will also affect the normal work of solid lubricant. The biggest difference between graphene and MoS_2 is that graphene is a zero band gap and MoS_2 can change from indirect band gap to direct band gap by decreasing its thickness. Therefore, the adjustable band gap performance and the traditional solid lubricant make the electrical and mechanical properties of MoS_2 valuable for application. Strelcov et al. [13] took a variety of metal salts as the research object, and found that the friction force in the electric field was gradually becoming larger. Shin et al. [14] unveiled the nano-scale frictional properties of contacting with curved liquid surface under the action of external electric field. The water molecule reacted under the

* Corresponding authors at: School of Mechanical Engineering, Jiangsu University, Zhenjiang 212013, China (Q. Wang), State Key Laboratory of Tribology, Department of Mechanical Engineering, Tsinghua University, Beijing, 100084, China (G.X. Xie).
E-mail addresses: qwang@mail.ujs.edu.cn (Q. Wang), xgx2014@tsinghua.edu.cn (G. Xie).

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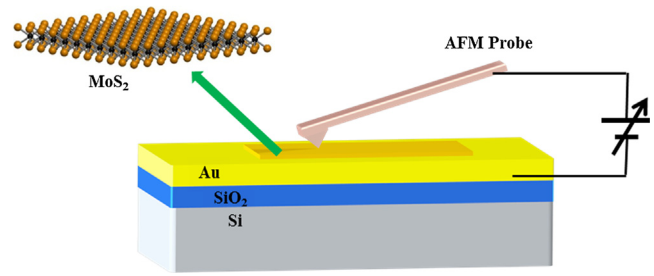

Fig. 1. Schematic diagram of the principle of normal electric field on of MoS_2 nanosheets.

action of electric field so as to control the friction.

In this work, we report a comprehensive study of friction and wear characteristics of MoS_2 by conductive AFM applied with electric field. MoS_2 samples were mechanically stripped flakes from single to few layers. A conductive probe was employed to test the friction force of MoS_2 nanosheets. And we investigated the topography, surface potential the friction of MoS_2 under different bias. In addition, the wear of MoS_2 under different load and bias was also demonstrated.

2. Experimental methods

A conductive substrate was fabricated by coating on a wafer with a layer of 300 nm thick silicon oxide, and the coating was plated from top to bottom with Cr and Au film with the thickness of 20 nm and 80 nm, respectively. The optical image of the sample is shown in the supporting information Fig. S1.

MoS_2 nanosheets was obtained by mechanical exfoliation method, and was transferred onto the substrate. The blue film tape was attached to the surface of a small number of bulk of MoS_2 crystal. Then the tape was gently pressed so that the MoS_2 firmly to the tape and slowly peeled off. The adhesive tape surface adhered to a thin layer of MoS_2 sheet, and this process was repeated for 3–5 times. The PDMS film was then gently pressed to the tape of the MoS_2 nanosheets. Following, the MoS_2 was transferred to the Au substrate through the PDMS film. Because of the poor adhesion between the metal and MoS_2, the substrate was placed at 50 °C on the heating plate platform for 10–20 s. Finally, PDMS film was slowly torn to get the experimental samples.

Before the AFM experiments, the suitable MoS_2 nanosheets were selected with optical microscope. AFM imaging was performed using the Cypher S (Asylum Research) atomic force microscope. In order to avoid the interference of the external environment to the experimental result, the temperature and relative humidity in the laboratory were kept at 20 °C and ~20%, respectively. The height and friction images of the MoS_2 nanosheets were obtained by using the lateral force mode of AFM. The frictional variation of the nanosheets under experimental conditions was observed. The phase images and surface potential images of the nanosheets were explored by using the electrostatic force mode. The AFM experiment of the friction force was operated by using FMG01/PT conductive probe. For the experimental parameters of the probe, the improved wedge calibration method was adopted to convert the bias signal data into force data [15]. The obtained torsional constant was 1187 nN/V for the FMG01/PT probe used in this work. Schematic diagram of applying the normal electric field onto MoS_2 is shown in Fig. 1.

During the experiment of the friction force of MoS_2 nanosheets with the applying normal electric field, we selected an area containing multiple different thicknesses, which is to unveil the effect of electric field on the friction force of MoS_2 of different thickness. As shown in Fig. 2, a MoS_2 nanosheets with a gradient was obtained by using the mechanical exfoliation method. It can be found that the thin layer MoS_2 nanosheets with gradient (single-layer and few layers), with the thinner layer of MoS_2, the darker in the topography image, and the brighter the corresponding area of friction image, the greater the friction force. At room temperature, using the Cypher S-type (Asylum Research company) AFM, when the normal load was constant to 28 nN (set point = 1 V), the friction force of the thin layer MoS_2 nanosheets was changed by employing a conductive probe to exert the bias and changing the tip bias. The friction force was determined by selecting the region of the scanning region, and the average friction force was obtained for the selected frame area. The scanning rate was 5 Hz.

Furthermore, during the experiment of the wear of MoS_2 nanosheets with the applying normal electric field, the entire wear experiments process was performed on the AFM. By using the sliding contact between the AFM conductive probe and the MoS_2 nanosheets, the change of wear area was studied in different bias. Wear experiment schematic diagram is shown in supporting information Fig. S2. We selected a 1 μm × 1 μm area. The wear experiments based on the AFM scratching method were carried out. Each experiment lasted for 50 cycles in each square domain, and it means the probe slid 50 times at any given point in the wear domain. The scanning frequency for all the wear experiments was 10 Hz. Then the scanning domain expands to 2 μm × 2 μm area, contrasting the topography and friction of the Region 1 and Region 2 of the MoS_2 nanosheets. Next, other appropriate area was selected to repeat the wear experiment. The effects of different bias and loads on the friction and wear of MoS_2 nanosheets were illustrated by comparing the experimental results. The scanning rate of the AFM probe during the whole wear process was 10 Hz.

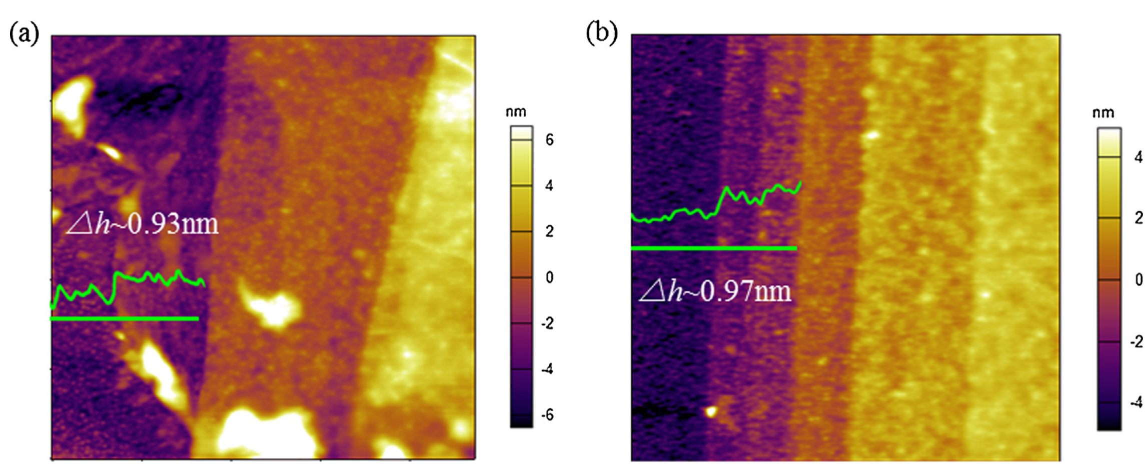

Fig. 2. The AFM topography images of a step-like thin layer MoS_2 nanosheets. (a) The topography image of the MoS_2 nanosheets in the experiment with the AFM tip applied bias. (b) The topography image of the MoS_2 nanosheets in the experiment with the Au substrate applied bias.

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